Summary of Muon Working Group

The Muon Trio

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B. Lee Roberts
Department of Physics
Boston University

roberts@bu.edu http://physics.bu.edu/roberts.html

The Muon Trio

- Lepton Flavor Violation

$$\mu^- A \to e^- A$$
$$\mu^+ \to e^+ \gamma$$
$$\mu^+ \to e^+ e^- e^+$$

- Muon EDM

$$\bar{u}_\mu \left[\frac{ie}{2m_\mu} f_2(q^2) - f_3(q^2)\gamma_5 \right] \sigma_{\beta\delta} q^\nu u_\mu$$

$$f_2(0) = a_\mu \quad f_3(0) = d_\mu; \text{ EDM}$$

- Muon (g-2)

chirality changing

$$\bar{u}_\mu [e f_1(q^2)\gamma_\beta + \frac{ie}{2m_\mu} f_2(q^2)\sigma_{\beta\delta} q^\delta] u_\mu$$

$$f_1(0) = 1 \quad f_2(0) = a_\mu$$

General Statements

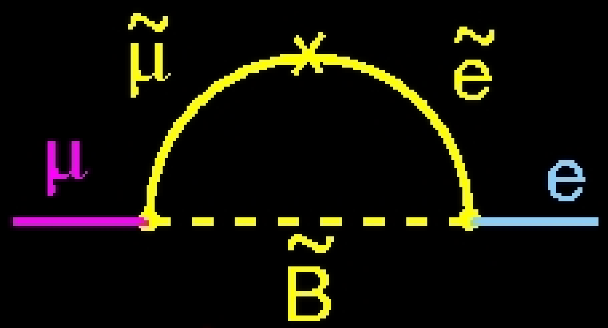
- We know that ν oscillate
  - neutral lepton flavor violation
- Expect Charged lepton flavor violation at some level
  - enhanced if there is new dynamics at the TeV scale
    - in particular if there is SUSY
- We expect $\cancel{CP}$ in the lepton sector (EDMs as well as ν oscillations)
  - possible connection with cosmology (leptogenesis)

The Physics Case:

- Scenario 1
  - LHC finds SUSY
- All three will have SUSY enhancements
  - to understand the nature of the SUSY space we need to get all the information possible to understand the nature of this new theory

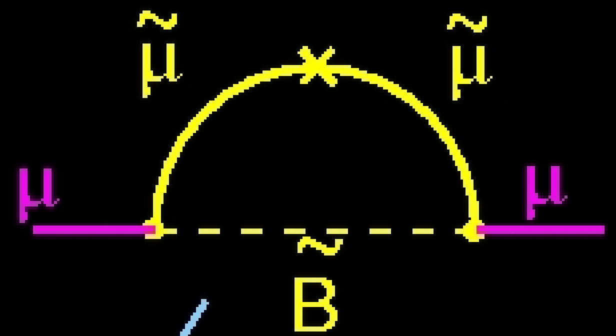
SUSY connection between a_μ, D_μ, $\mu \rightarrow e$

$\mu \longrightarrow$ **e**



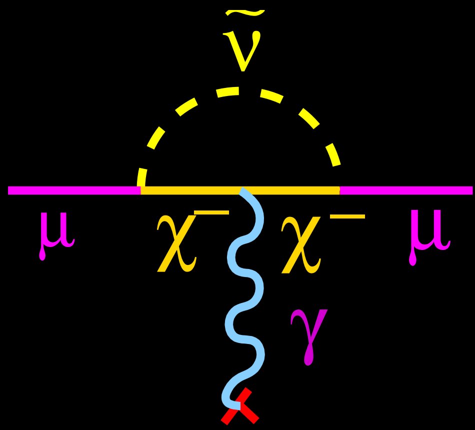
MDM

EDM



$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

a_μ sensitivity to SUSY (large $\tan\beta$)



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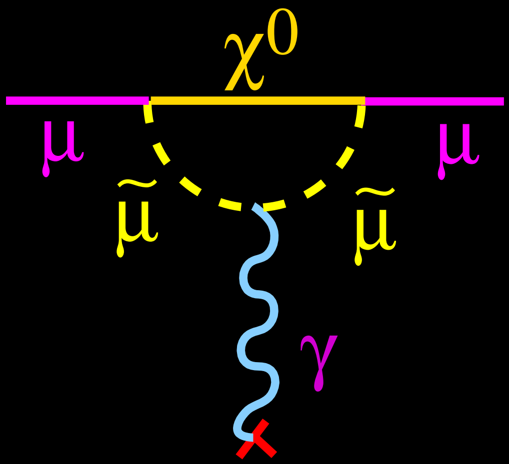


$$a_\mu(\mathrm{SUSY}) \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \left(1 - \frac{4\alpha}{\pi} \ln \frac{\tilde{m}}{m_\mu}\right)$$

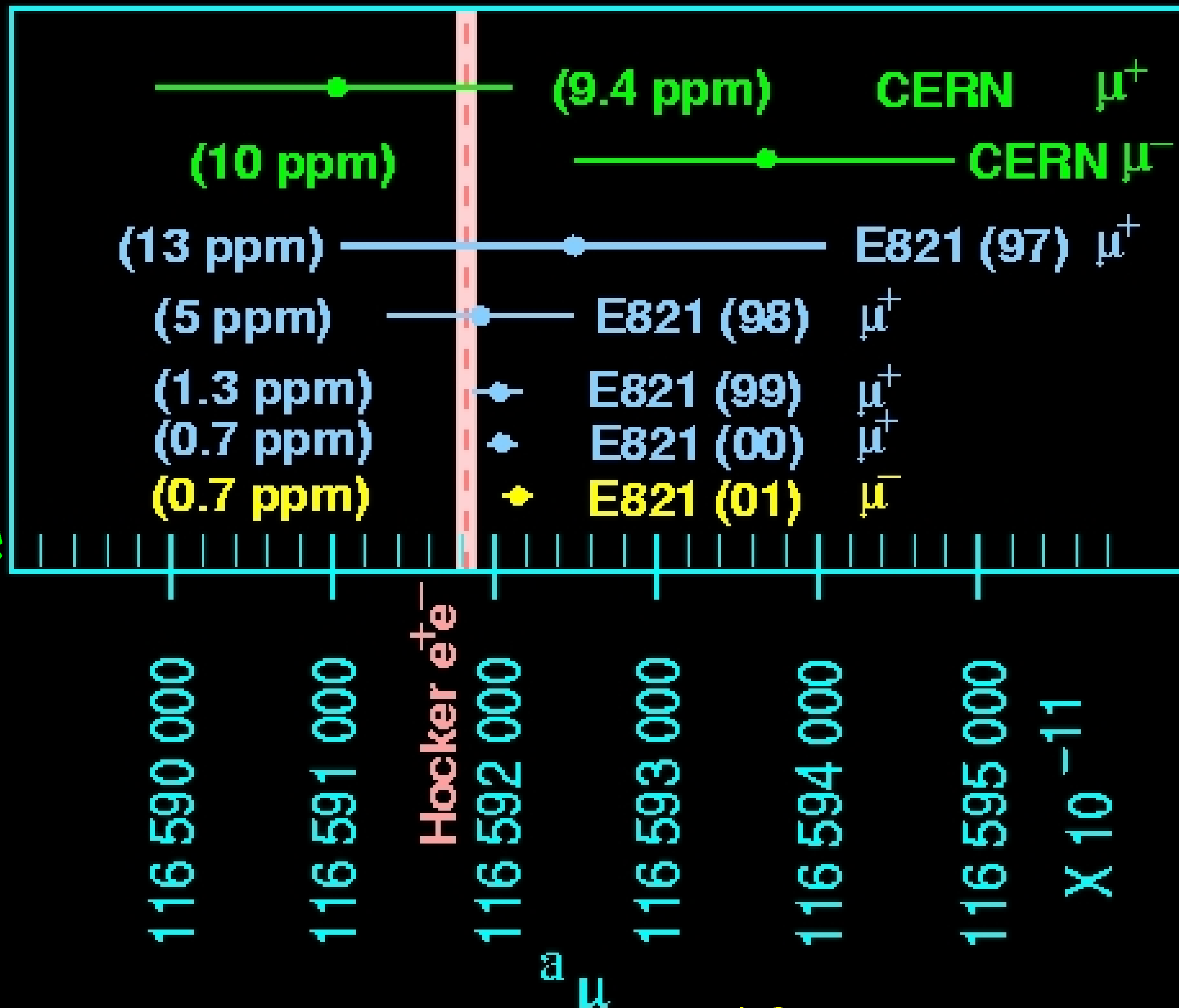
$$\simeq (\mathrm{sgn}\mu)\ 13 \times 10^{-10}\ \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

Today with e^+e^- based theory:

All E821 results were obtained with a “blind” analysis.

2.7σ difference with e^+e^- SM value

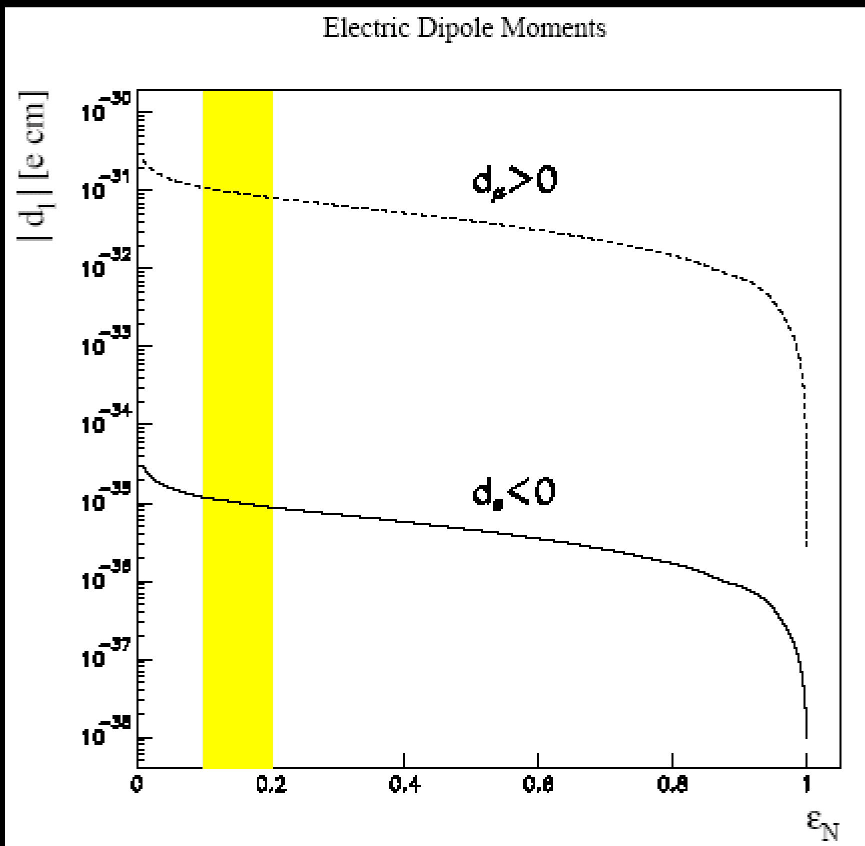
$$a_\mu = \frac{\omega_a}{\frac{e}{mc}B}$$



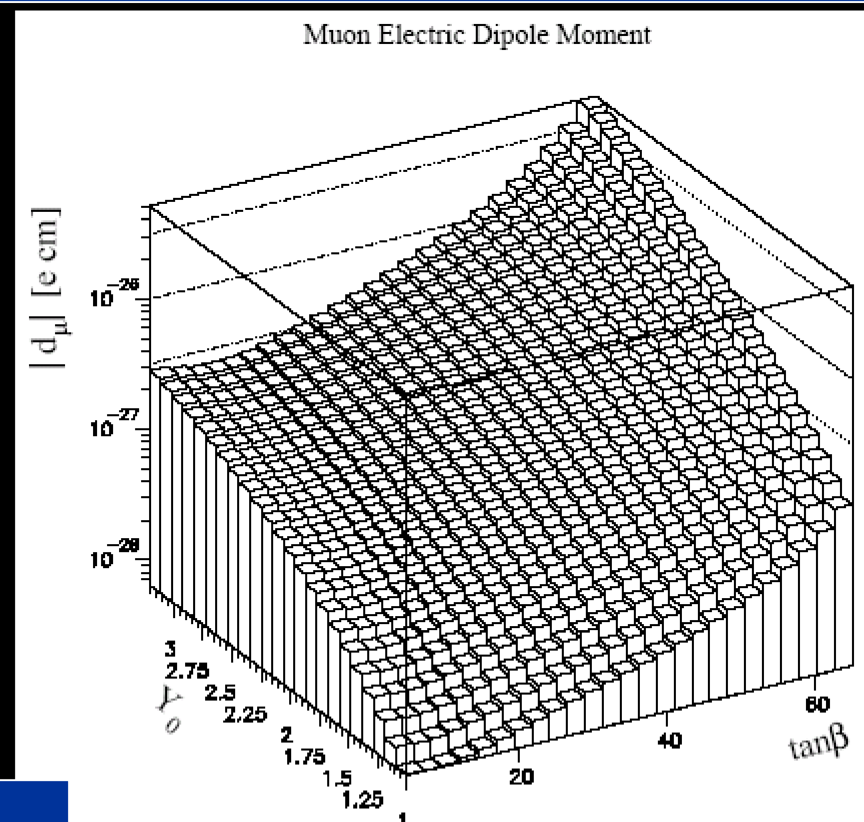
$$a_\mu = 11\,659\,208(6) \times 10^{-10} \ (0.5\,\text{ppm})$$

Model Calculations of μ EDM

μ EDM may be enhanced above $m_\mu/m_e \times$ e EDM



Magnitude increases with magnitude of ν Yukawa couplings and tan β



arXiv:hep-ph/0111324 v2 30 Nov 2001

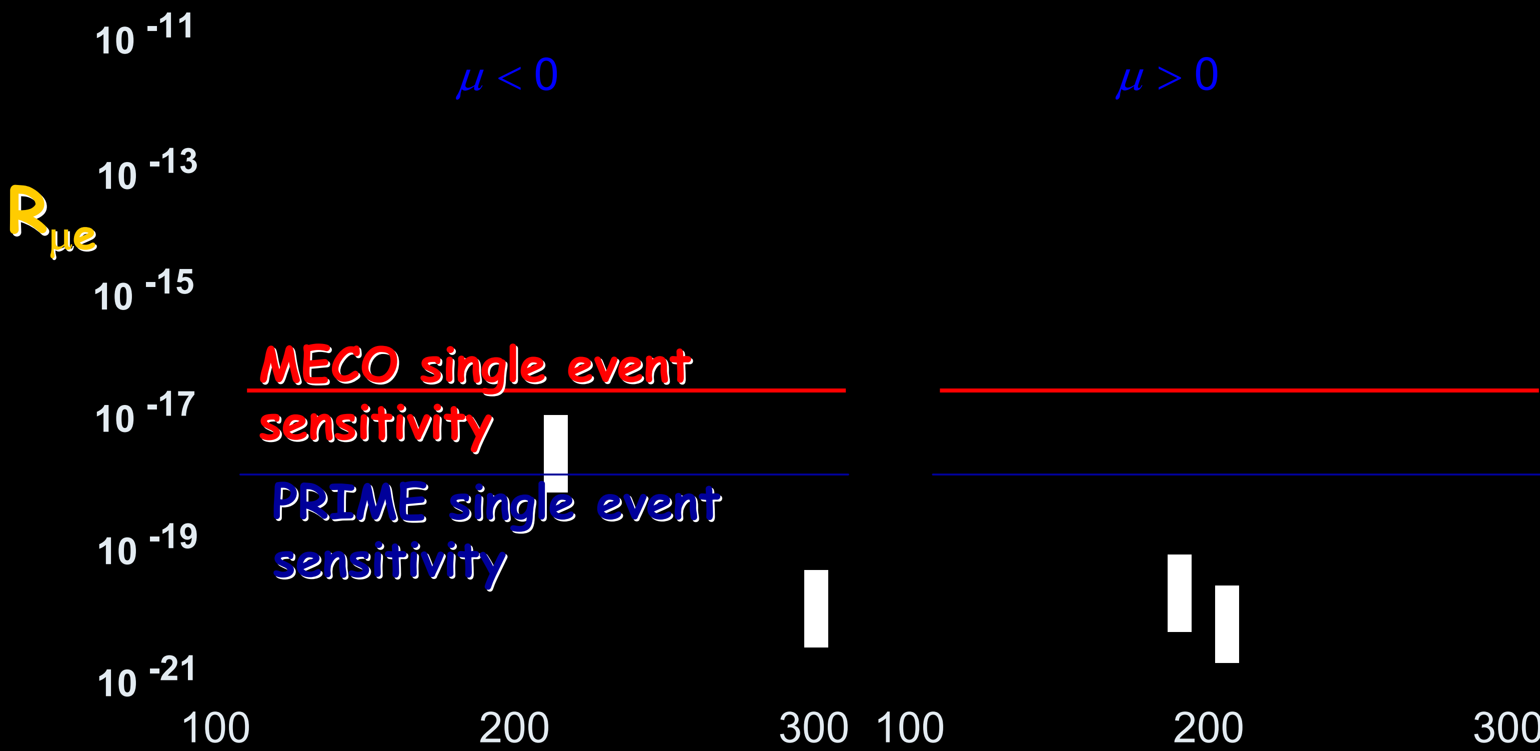
μ EDM greatly enhanced when heavy neutrinos non-degenerate

Present EDM Limits

Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
n	6.3×10^{-26}	$10^{-32} - 10^{-31}$
e^{-}	$\sim 1.6 \times 10^{-27}$	$< 10^{-41}$
μ	$< 10^{-18}$ (CERN) $\sim 10^{-19}$ * (E821)	$< 10^{-38}$
future μ exp	10^{-24} to 10^{-25}	

*projected

SUSY predictions of $\mu^- A \to e^- A$



From Barbieri, Hall, Hisano ...

$\mu \to e\gamma$ & $\mu^- A \to e^- A$ Branching Ratios are linearly correlated

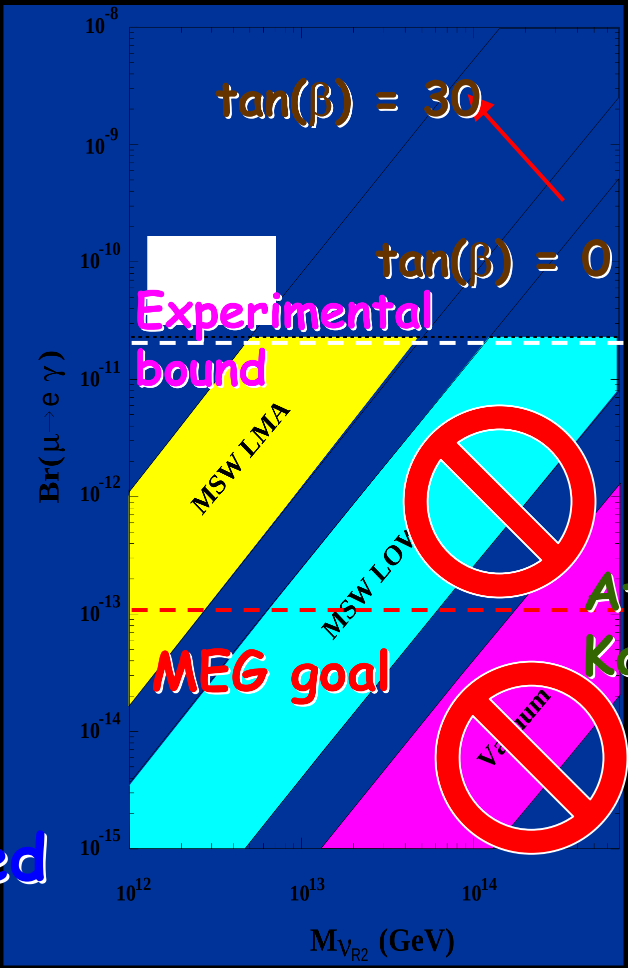
$$\frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\mu A \to eA)} \approx 200 \div 300$$

Complementary measurements (discrimination between SUSY models)

Connection with ν oscillations

Additional contribution to slepton mixing from V_{21}, matrix element responsible for solar neutrino deficit. (J. Hisano & N. Nomura, Phys. Rev. **D59** (1999) 116005).

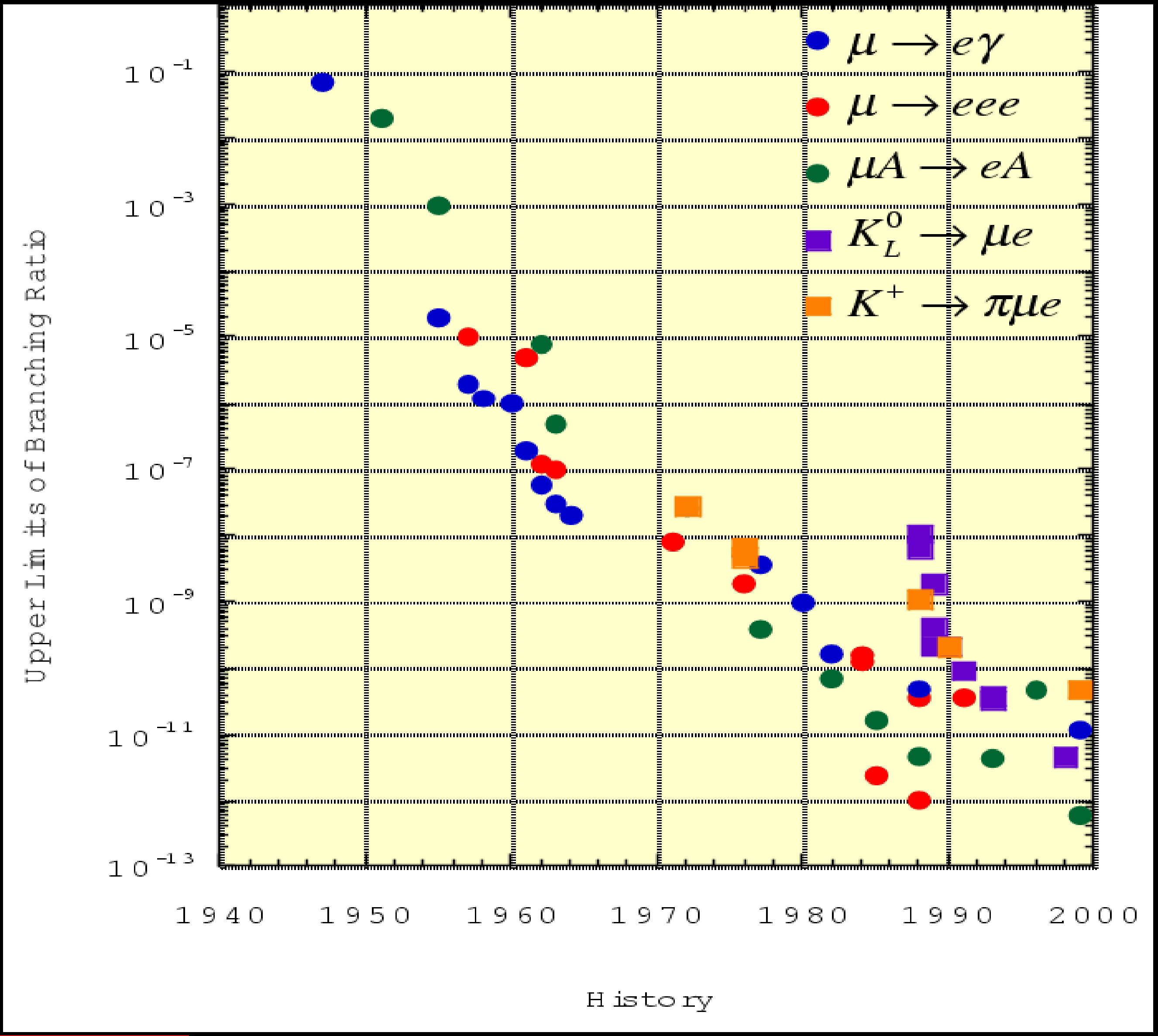
Largely favoured
and confirmed by Kamland



After Kamland

All solar ν experiments combined

History of LFV Limits



The Physics Case

- Scenario 2
  - LHC finds Standard Model Higgs at a reasonable mass, nothing else, (g-2) discrepancy could be the only indication beyond neutrino mass of New Physics
- Then precision measurements come to the forefront, since they are sensitive to heavier virtual physics.
  - *μ-e* conversion is especially sensitive to other new physics besides SUSY

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$

Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L =$

$3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2

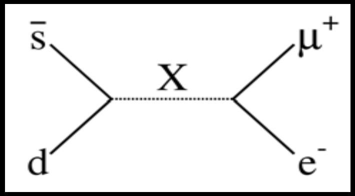
Heavy Z’, Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

Limits on Muon Number Violating Processes



		Mass limit
$\Delta G=0$	$B(K_L^0 \to \mu^\pm e^\mp) < 4.7\times10^{-12}$	150 TeV/c²
	$B(K^+ \to \pi^+\mu^+e^-) < 4\times10^{-11}$	31 TeV/c²
	$B(K_L^0 \to \pi^0\mu^+e^-) < 3.2\times10^{-10}$	37 TeV/c²
$\Delta G=1$	$B(\mu^+ \to e^+e^+e^-) < 1\times10^{-12}$	86 TeV/c²
	$\boxed{B(\mu^+ \to e^+\gamma) < 1.2\times10^{-11}}$	21 TeV/c²
	$\boxed{\dfrac{\Gamma(\mu^- A \to e^- A)}{\Gamma(\mu^- A \to \nu A')} < 6.1\times10^{-13}}$	365 TeV/c²

$\mu^- N \rightarrow e^- N$ vs. $\mu \rightarrow e\gamma$ as Probes of LFV

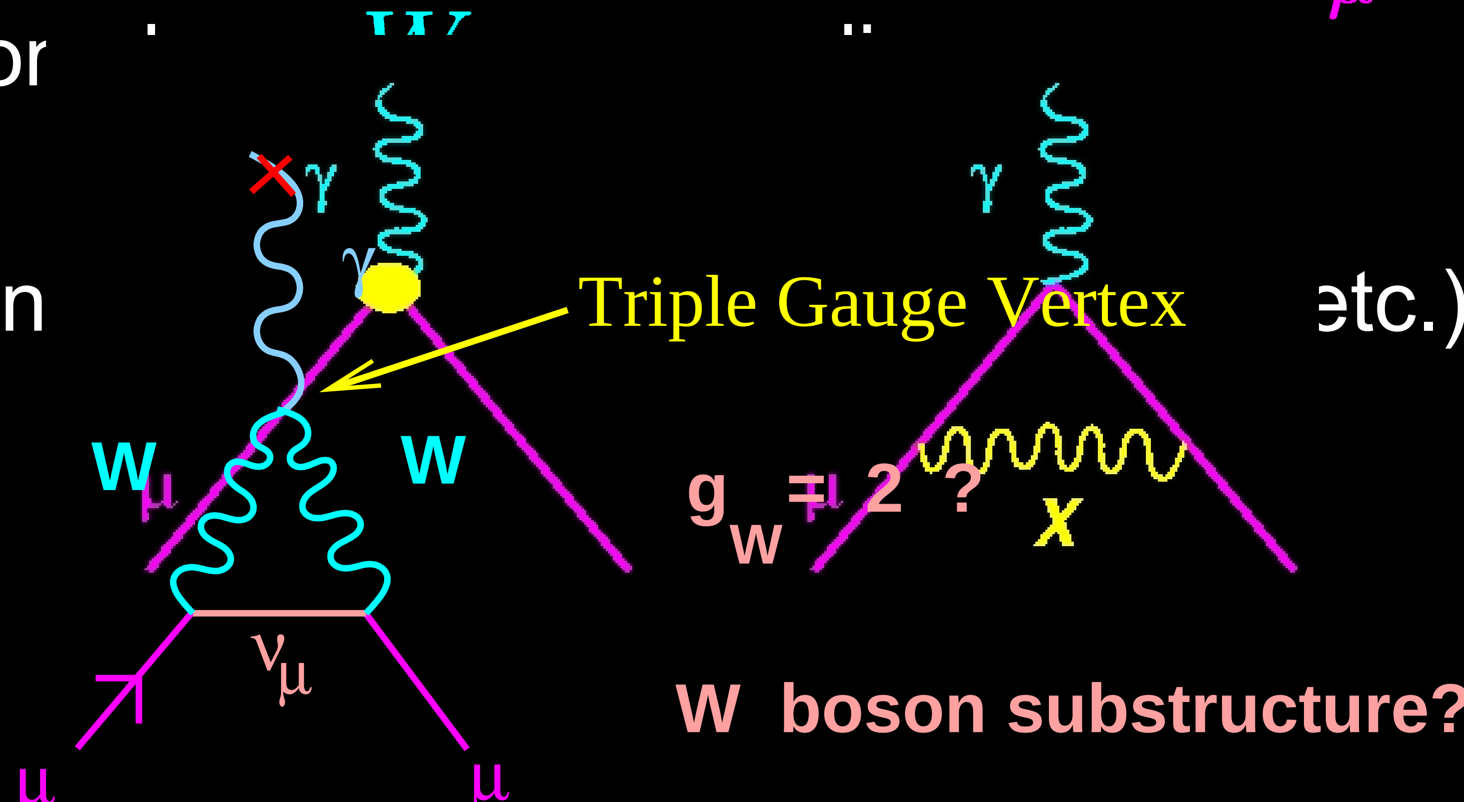
- $\mu^- N \rightarrow e^- N$ is more sensitive for essentially all processes not mediated by photon
- $\mu^- N \rightarrow e^- N$ is more sensitive than is $\mu \rightarrow e\gamma$ to chirality conserving processes
- $\mu \rightarrow e\gamma$ is more sensitive for processes mediated by photons
  - $B(\mu \rightarrow e\gamma) \cong 300 \times R_{\mu e}$ for these processes
- The motivation is sufficiently strong that both experiments should be done
  - Relative rates for $\mu \rightarrow e\gamma$ and $\mu^- N \rightarrow e^- N$ would give information on underlying mechanism
  - A significant rate for $\mu \rightarrow e\gamma$ with polarized muons could give additional information on mechanism

a_μ is sensitive to a wide range of new physics besides SUSY

- muon substructure

$$\delta a_\mu(\Lambda_\mu) \simeq \frac{m_\mu^2}{\Lambda_\mu^2}$$

- anor
- man etc.)



The Experiments: LFV

$$\mu^- A \to e^- A$$

$$\mu^+ \to e^+ \gamma$$

$$\mu^+ \to e^+ e^- e^+$$

$$\mu^+ e^- \to \mu^- e^+$$

- μe conversion and Muonium-anti-Muonium conversion
  – pulsed beam
- $\mu \to e\gamma$ and *eee*
  – DC beam

Present Experiments on LFV

- MEG
  - 10^{-13} BR sensitivity
- MECO
  - 10^{-17} BR sensitivity

Future Experiments on LFV

- PRIME-type experiment (with FFAG muon storage ring)
  - few X 10^{-19}
- $\mu \rightarrow e\gamma$ or $\mu \rightarrow eee$ experiment , $\rightarrow$???

Accidental limited: $BR_{acc} \propto R_{\mu} \times \Delta E_e \times \Delta E_{\gamma}^2 \times \Delta\theta_{e\gamma}^2 \times \Delta t_{e\gamma}$

Unique Features of PD

- the ν program uses Main Injector
  - a program using the recycler @8 GeV could have 588 bunches, 1500 x 10^{12} protons (0.2 tp/bunch); pulse width 3 ns, with the ability to kick one bunch at a time.
- This is perfect for μe conversion, muon EDM, and other μ experiments which need a pulsed beam. (except g-2 which needs 6 GeV/c π)
- This μ program could run simultaneously with the (high E) ν program.

Spin Precession Frequencies: EDM & g-2

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

ω_a

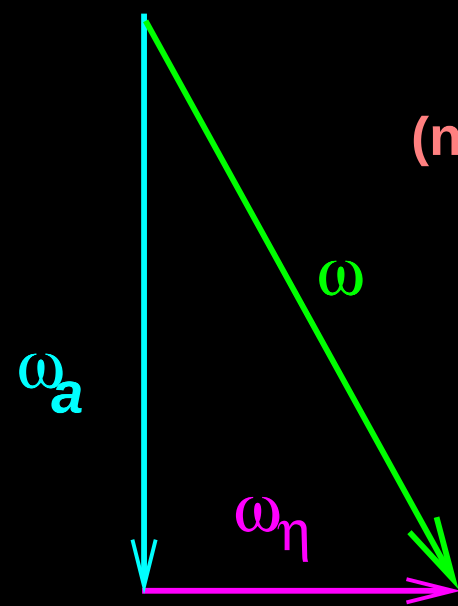
$$+\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

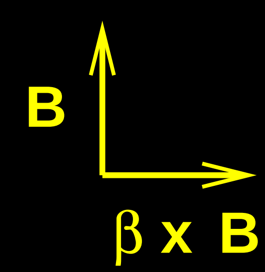
ω_η

$$\gamma_{\text{magic}} = 29.3$$

The motional E - field, β X B, is **much** stronger than laboratory electric fields.

(not to scale)

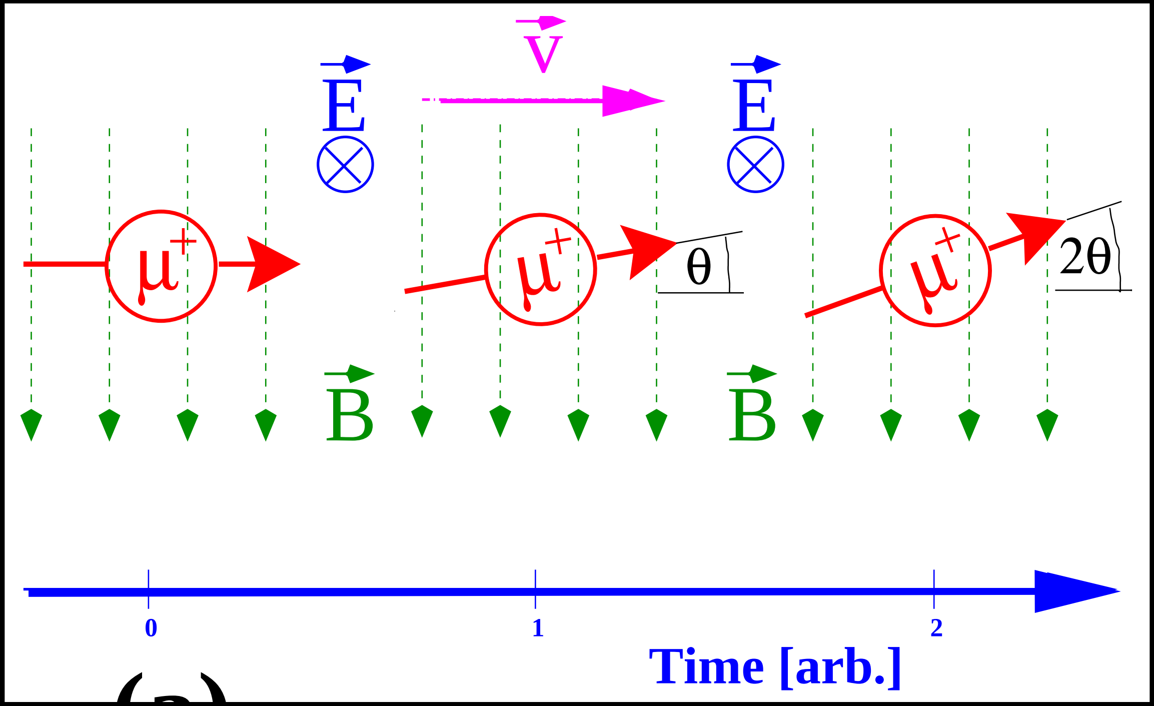




The EDM causes the spin to precess out of plane.

Muon EDM

- use radial E field to “turn off” g-2 precession so the spin follows the momentum.
- look for an up-down asymmetry which builds up with time



Beam Needs: NP^2

- the figure of merit is N_μ times the polarization.
- we need $$NP^2 \sim 5 \times 10^{16}$$

to reach the 10^{-24} e-cm level.

- Since SUSY calculations range from 10^{-22} to 10^{-32} e cm, more muons is better.

g-2 future progress

- E969 @ BNL   0.5 → 0.20 ppm
  - expected near-term improvement in theory, → the ability to confront the SM by ~ x2
- The next generation 0.20 → 0.05 ppm
  - substantial R&D would be necessary
    - new ring or improved present ring?

Other fundamental measurements:

- LFV $\mu + N \rightarrow \tau + X$
  - might be competitive with LFV τ decays
- Measurements with Muonium
  - $m^+ e^- \rightarrow m^- e^+$ conversion
  - measurement of M hyperfine structure (μ_μ/μ_p)
  - measurement of fine-structure constant α
  - m_μ/m_e
- Muon lifetime
  - G_F

Summary and Conclusions

- Important muon experiments can be carried out at the Proton Driver
  - LFV
  - g-2
  - muon EDM
- There are a few smaller scale experiments which also would benefit from such an improved intensity.

Conclusions – ctd.

- The muon trio are <u>complementary</u> to other ways to explore the frontier beyond the standard model
- Depending on what LHC finds, they may be the only way to get at this information.
- In either case, they will provide essential information in our attempt to discover the correct theory beyond the Standard Model